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Distributed Sensors

Recent technological discoveries in distributed systems, new clustering and networking protocols in conjunction with progressing wireless, Internet and new smart sensors, have led us to move towards more intelligent sensor solutions for which we expect a growing global demand and new range of superior applications to promote our next stages of technology for a new social and economical development paradigm. In order to achieve this unique opportunity for a maximum global impact using minimum resources we need to harmonise our global, regional and local industrial and academic efforts at all levels under the common goals of sensor enabled smart media distributed systems.

1.1 Primary Objectives

Due to the service nature of sensor technology and its firm market relationships with other technologies in many aspects of our modern life in an ever-growing industrial world, one can visualise the sensitivity, if not dependability, of our social and economical developments to the sensors. Our understanding of this technology can be greatly influenced by the choice of one out of two extreme views of sensors.

First view: they are regarded as transducers, simple converters of a signal or data from one form into another, a more suitable format. The second view: they are regarded as intelligent proactive devices as part of a larger system where sensing plays an important role in bringing in a new layer of control and intelligence over our capabilities in managing various aspects of our life, including health, stability and security for better social and economical prosperity. That is, under the first view, a traditional understanding of the sensors, our poor vision of the sensor technology imposes excessive limitations to smart sensors functionalities. Therefore for their uses in the real world we may fail to justify our existing overwhelming investments on new smart sensor associated research and development projects. The second

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Habib F. Rashvand and Jose M. Alcaraz Calero.

view is, however, more acceptable to such an investment as its integration with other systems can add new exciting dimensions to new systems, applications, services and to their applicability to make sensors to help to deploy new breeds of intelligent distributed systems. This would enable further agility, efficacy and product viability to deliver new applications of distributed intelligent sensors providing a new range of versatile solutions enhancing every aspect of our modern life today.

For the second view, we therefore set the book's primary objectives following on from our preliminary discussions. Part of this discussion is associated with a demonstration of the above mentioned practical capabilities of intelligent sensors for which we need to understand some fundamental concepts of these new sensors, appreciate their critical factors for practical deployment whilst we visualise the viability of a new generation of sensors being developed under the protection of innovation where their needs, applications and potential market forces dominate over any lengthy theoretical details of the applied technologies.

In order to make our objectives clearer we review the three main components of a successful innovation, namely: (a) feasibility of the innovative technological solution; (b) viability of the solution, that is the need and potential requirement of the solution; and finally; (c) the success factors, that is acceptability test as in pilot studies and introduction of the new product being an unpredictable product, system or service to the users.

For the requirements of (a) and (c) we have many typical application solutions for adopting the new sensors and verification of their superior features that is throughout five chapters in Chapters 4 to 8 of this book, all enriched with discussions on real and practical applications and case studies enhanced with a variety of experimental results reported by researchers from innovative research laboratories to industrial production lines. For the market requirements and needs of (b) we look into the potential markets under two different sets of categories of the need and service sectors. In the first set we look at 'user need' aspects of distributed sensor systems (DSS) answering the question of 'what sensor systems can do for us'? We then have a closer look at a categorised DSS market for the visualisation of the growing potential markets for emerging sensor-centred intelligent products and services.

1.1.1 User-Based Category

As a response to the question of 'what new sensors can do for us' we identify the following seven generic uses:

Sensor for Monitoring

This feature-based usability is an enhanced use of traditional sensors as an embedded sensing parametric visibility for monitoring critical variables of a system or media of interest. Also a new response to the need for:

- low energy global scale monitoring systems;
- low cost global scale monitoring uses;
- regular data collection applications;
- statistical measurement systems;
- monitoring behaviour system applications;
- location identification;
- ad hoc style information gathering;
- monitoring health and well being;
- monitoring for emergency cases and interventions.

Smart Media

Upon the philosophy of intelligent environment or ambient intelligence many industries, that is electrical, physical, chemical or biological, can now be upgraded using new smart intelligent sensors. Typical broad application areas are associated with the following:

- smart stationery;
- smart home;
- smart office;
- interactive communication enabler;
- behavioural and reactionary functionalities;
- provision of service pre processing;
- data processing, manipulation and ubiquitous environment;
- preparation of information or specifically treated signals;
- information selectivity and effective databases.

System Controllability

As sensor systems grow larger, providing more desirable functions, the more complex they become. Then, in many cases without any regular check-ups, no refined adjustments can be identified leading to a poor status of performance and in some cases they may become unstable. To solve such a growing problem some elements of control could always be desirable, for example:

- sensor-actuator-enhanced systems can provide tight control over few critical components of a system;
- a complex system behaves differently with time;
- extending systems' useful life is always desirable;
- systems using time-variant components require regular tuning;
- many practical systems do not behave perfectly per design, some have side effects and some require extra resources to maintain a proper run. Due to the nature of the problem, these imperfect behaviours grow in time affecting the viability of

the system, which may lead to its obsoleteness, if still stable. We can easily extend a system's life and enhance its stability by adopting integrated intelligent sensing using programmable devices.

Remote Sensor-Actuator Agent

With the rise of globalisation the shape of industries is changing rapidly towards two sustainable equilibriums of:

- Small medium enterprise (SME) style small service industries;
- Agile and globally competitive industries.

The second group of industries should characterise the future of our industrial societies. They include new agile manufacturers, system integrators and distributors who could benefit from enhancements for their remote monitoring, remote configuration and remote control using autonomous embedded technologies. To these industries and many global service providers use of integrated sensor-actuator counts as a major advantage for their market competition enabling them through two basic cost cutting competitive edges of, (a) remote sensing to identify the status of a system and, (b) remote actuation to implement a change without excessive costly visits of the experts.

Dependability

Whilst the impact of globalisation is increasing many new disturbing activities such as the number of computer crimes is on the rise at alarming rates. Whereas, a better use of a distributed security integrated solution using a multi-agent system or intelligent sensor system would be reducing the cost and number of surveillance, casualties and enhancing the global trust (Rashvand et al., 2010).

Sustainability

Depletion of earth resources, frequent massive destructive disasters and a continually changing environment worry many intellectuals, which may result in a demoralisation of public views on the governing bodies. This may also change people's view for supporting future technological developments. To change this trend and reduce the casualties may help to ensure sustainability of life on earth for which we need to establish more effective global monitoring systems to help us deal with:

- Habitual life – the uneven distribution of the population is causing deterioration by the disappearance of valid and healthy villages due to lack of governmental support for their basic needs.

- Urbanisation – pressing issues all over the world of an increasingly poor quality of life for an unachievable expected high-life due to numerous pressures imposed on a large population in poorly organised cities.
- Release of waste and uncontrolled poisonous polluting gas and chemicals causing long-term degradation of life.
- Ongoing human casualties and poverty and the impact of uncontrollable natural disasters.
- Depleting earth's scarce natural resources.
- Poor quality of health due to growing age, growing traffic in heavily congested populated areas with maximum effects on the majority of people.
- Risky and unhealthy habitual activities.

1.1.2 Sector-Based Category

Another way of looking at our needs for sensor-based potential intelligent DSS products, upon maturity of the new cost effective, energy efficient advanced sensors, which enables emerging super mass production capabilities in connection with new advances in wireless, Internet and distributed intelligence technologies, we can broadly categorise five groups as follows:

- Environmental Applications – DSS for greener life and sustainable climate and monitoring earth resources.
- Industrial Applications – automation, heavy economy as an infrastructure for improving the quality of life whilst minimising costs and overheads.
- Medical Applications – surgical, physiological, psychological, increasing age and a higher quality of life.
- Security and Surveillance – safety, immunity, trust, dependability.
- Old Age and Well Being Applications – a growing market with significant pressures on most nations and more on those with social security supports.

Extensive discussions for the above-mentioned categorised applications are included throughout the book with many detailed cases studies and application scenarios in the later parts, Chapters 4 to 8.

1.1.3 Primary Objectives

Now we are in a position to introduce *the book's four primary objectives* and to explain why we have adopted our style of presentation and why we believe this is the best way for the reader to acquire the highest degree of required knowledge using a single volume with the minimum expense of their time to adopt intelligent DSS for their further uses: (a) design of a new application; (b) integration of DSS with another distributed system; (c) engaging in an investigation or product development or (d) conduct a project management for a DSS based service deployment.

Objective 1. Generic Smart Sensing

- In order to capture the maximum use and popularity for deploying DSS on a global scale we provide an in-depth description of new, intelligent sensing devices. This includes the architecture of two or more basic core processing units, one for less flexible, extremely low cost programmable generic functions and a few for smaller size mass production for common application specific features.
- Smart media approach to the future technological developments. With new smart sensors we can embed minimum specific intelligence in various parts of the media for a variety of uses and applications including regular monitoring, intelligent response per request, automatic report generation or systems requirement for actions and warnings.
- Additional global market viability features of the applications are where we can trim off the hardware complexity whilst adopting more flexible blocks in the form of off-the-shelf middleware functions.

Objective 2. Intelligent Specific Sensing

Technical productivity and the natural intelligent features of distributed sensing such as ubiquitous networking, clustering, beamforming, sensor fusion and distributed intelligence make DSS applications superior to all existing smart sensor systems. Though all details are not in the scope of this book we highlight a few specific features of the new generation of intelligent sensors, for example:

- Clustering features a very basic superiority of DSS by providing uniquely efficient target proximity for the point-of-interest (PoI) and facilitating superior fusion for the sensing information collected from the media. This feature provides considerable advantages for two basic functions of data and mobility for a wide range of applications over wireless-only, wired-only and mixed wired-wireless distributed sensors.
- Beamforming features a basic superiority of DSS over the wireless media providing unique directivity and selectivity, where cooperative sensors in an array adjust their antennas configurations automatically to coordinate for a combined transmission lobe towards the target or PoI in the media for the two most effective outcomes of (a) maximum use of transmitted power and (b) minimum interference with other channels and other sensors in the system.
- Exploring the distributed intelligence features the DSS to be able to be integrated with other data oriented intelligent systems such as multi-agent system (MAS), enabling new superior integrated solutions for precision, trust and effectiveness.

Objective 3. Innovation Approach

- Analysing the need for investment in a global scale smart sensor product development project one normally starts with initial market research investigating the viability and success factors of the technology. For this we include innovative features of DSS products including their superiority over the two previous generations as in the first two 'objectives' with a better understanding of market segmentation and its distribution statistics. Then the decision for the investment merely becomes as simple as cost for mass production, cost per unit, returns on investment projection, maturity of the technology and new features of soft production.
- Due to the economical sensitivity of DSS for a sustainable global development and better economical progress we encourage industrial nations along with global organisations to help with this unique adoption of DSS based technological development.

Objective 4. Learning by Example

Learning by example is our adopted approach to maximise the reader's fast understanding of the underlying technological aspects of a versatile and complex system like DSS, without going through volumes of details which one may need for a successful deployment of an application or general understanding of its potential uses and services. This method can also inform both educators and practitioners of the availability of a viable technology in one compact volume about a system which is involved with well over half of the future economy dependent technologies.

Based on our previous discussions in this chapter and upon our four objectives we structure the remaining part of the book. To achieve these objectives through brief but effective materials provided in the remaining part of this and its seven following chapters. In the remaining part of this chapter we examine the basic aspect of the DSS including a brief introduction of the new sensors and actuators covering innovation, distributed intelligent and classification of the DSS applications, where we look for key technologies such as smart and intelligent sensors. Chapter 2 looks into device-based smart sensors with some interesting further classification of sensors. Chapter 3 provides insight into selective smart sensor networking, infrastructure and advanced techniques used in the device-based structure for new generations of smart sensors. The rest of the book consists of five chapters, 4 to 8 covering typical scenarios for advanced applications of the DSS. First we look into medical and consumer applications with five novel case studies demonstrating some typical burning potential application areas of the DSS for the next 5 to 10 years. We then examine a few other application areas of the DSS including three case studies and some other typical applications of the DSS as the tip of the iceberg for upcoming market potential.

1.2 Historical Development

The science of sensing and its associated versatile technology today have been man's best friend since living in caves and enjoying an early agricultural lifestyle. Then, sensors were simple additional enhancement gadgets to their basic but effective collection of tools. Today we have superb multidisciplinary intelligent smart sensors offering something largely different, enabling our overwhelmingly complex systems to help build a sustainable global village.

In order to get a better grip of the new technology, before going any further one should know the answer to the question of 'What is a sensor?' Sensors, though often integrated into a bigger and much more complex system than themselves, represent a well-known technology virtually throughout all today's industries. The enormous range of applications they can offer vary from a humble thermometer checking a new born baby's body temperature to a complex system associated with the nucleus measuring devices of an elaborate radiation measurement system in an atomic reactor.

1.2.1 Sensing

In today's literature the word *sensing* has several meanings, but two most relevant ones are 'intelligence' and 'feeling'. Although both have their own specific projections in human life the first one comes with more relevance to the scope of this book. We can break the first one down further into 'rationality' and 'wisdom'. The combination of these two functions can be regarded as 'intelligent visibility', closely related to the survival of an intelligent human at his early stages of evolution enabling him to master the earth and to overcome the difficulties of a harsh life, to stand out against all the odds of nature, and cope with the inhospitable surrounding environment. This is also the case through the evolutionary process, with shortages of food and primitive shelters causing the spread of infectious diseases. Learning from nature, we then extend the human sensory system for use in our living environment through machines, systems and many other artefacts.

Biologists follow the physical processes of human nature to come up with our well known 'five groups of senses', commonly called human sensory systems associated with seeing, hearing, smelling, tasting and touching:

- Seeing – well known, well utilised (example: camera).
- Hearing – known, partly utilised (example: microphone).
- Smell – little known, some utilisation (example: enose).
- Tasting – little known, little utilised (example: chemicals).
- Touch Feeling – some known, some utilised (example: thermometer).

1.2.2 Historical Sensor Generations

Looking back into the staggering development of sensors over centuries of engineering effort it is possible to trace three distinct development trends for sensor applications, namely transducer sensors, smart sensors and our new intelligent device-based distributed sensors.

The first generation of sensors can be traced back to the early stages of civilisation. They include the actuators with sharp rises in development during the first and second technological revolutions. Due to the limited level of information processing and interconnection capabilities, the uses of these sensors are limited to the potential of their transduction function, where the cost, size and physical placement issues of the products dominate their use. Large, mechanical sensors, controlling actuators, physical sensors, chemical sensors, traditional biosensor, and heavy industrial sensors can be categorised under this generation. Due to the nature of development and versatility in their form, shape, media of application and uses we call them *traditional sensor transducers* (TST). It is easy to notice that, due to their need for continual improvements, most of them cannot make use of low cost mass production and therefore many of them are still developing for practicality factors such as shrinking in size, the cost to the user, and other suitability features.

The development of second-generation sensors started in the later part of the twentieth century and is approaching its peak in the latter part of the first decade of the twenty-first century. These sensor systems are commonly characterised by possession of a common architecture to accommodate the enhanced sensing features including embedded signal processing and light sensor specific computing and communication capabilities.

Their large-scale market enhancement becomes feasible when some basic processing features for carrying out common functions, such as networking, communications, basic data manipulations, low energy devices, application of specific selective smart processing adopted through advanced integrated circuit technology commonly processed in the electrical domain could be integrated.

Being called smart, these sensors are accommodated into small and very limited spaces and enhanced with common computing and communication functions. However, due to the fact that their limited Information and Communications Technology (ICT) features use single core architecture, the production technology naturally cannot respond to the sensor’s versatile global market requirements. That is, most of these original smart sensors need to include functions such as sensing specific signal pre processing, data gathering, data distribution, filtering, interference processing, and so on, on top of interfaces and communication protocols. In some cases extra processing, such as energy scavenging, clustering and media specific processes would increase the demand on the single core processor solution far beyond its capability or add cost, power, and so on, so that the extra shrinking boundary would push the originally estimated market into much smaller realistic margins. We therefore see the early sharp rise in both the volume and popularity of what are commonly called smart sensors followed rapidly with an early maturity and all successful integration of ASIC and VLSI solutions for small and miniature sensors went into a saturated market status. Having their applications and usability dominated and therefore characterised by their main basic device capabilities we

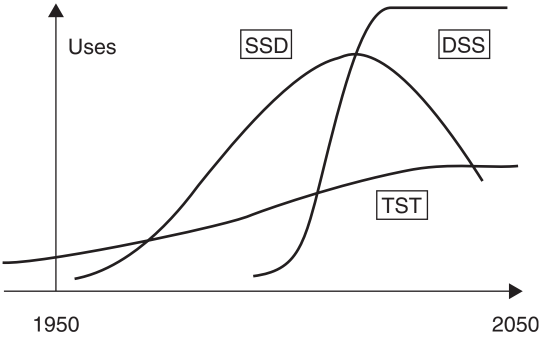

Figure 1.1 Historical developments of three generations of sensor: TST, SSD and DSS. The graphs are their estimated market viability.

therefore call them smart sensor devices (SSD). Some description of these sensors can be found in Chapter 2.

As we learn from the SSD early experiences, in some cases with much simpler media-based processing, some successful applications signify their smart functions to adopt a modularity approach with the capability of being integrated into larger systems should they pave their way up towards the third generation.

The third generation of sensor developments stems from distributed intelligence which makes another evolutionary change from the second generation. The arrival of many mass production oriented new applications under an enhanced architecture for DSS comes under a new cooperative approach for integrating a whole range of essential features into the system. The advanced architecture associated with the distributed approach brings elegant and superior features to sensor developments. As we discuss further details in Chapters 2 and 3, DSS is set to make the most of recent developments and incorporates unique new advantageous features of cooperative sensor and intensive use of distributed computing for intelligent sensor fusion, whilst freeing the production from traditional networking constraints, the limiting factors of previous generations. Figure 1.1 shows a relative estimated potential use of three distinct sensor generations upon their market viability at the global scale.

1.3 Trends and Technology

We address this section under two major views of *market development trends* and *technological developments*, which we have monitored over the last two decades.

1.3.1 Market Development Trends

There have been significant market-enabling social, economical and industrial developments all over the world during the last few decades, triggering many viable new uses of sensor systems for low cost mass production. It is, however, important to mention that a true cost reduction can be achieved only through a proper power integration of both the essential and most popular functions for maximum impact.

These functions would make these devices smart, and in many required cases intelligent enough to suit a much wider range of applications as they stay generic and adaptive enough to perform under variable conditions and changing application scenarios as required.

One should, however, bear in mind that, due to market trends, in many cases we should consider an additional cost for re-engineering and reconfiguration for deployment of the final stage implementation. This extra cost could sometimes grow extensively due to over-generalisation of the core processor, which in turn could push the overall cost to the user far beyond the basic production line.

In general the market boundaries for these systems are expanding rapidly from national or regional scales into global. This trend, however, imposes two new inter-related effects on the market: market size and the overall cost of unit product to the end user. Theoretically, the unit cost goes through a minimum, which strongly depends on two factors of basic mass production and the cost of post deployment service to the user. This minimum can be reduced extensively upon the degree of flexibility embedded in the core processor. That is, early smart sensors using a single core processor are too rigid to be able to find a place for very wide versatility and therefore the market size limitation may not support their position in a very competitive global market. The new generation of smart sensors, also called intelligent sensors using multi-agent technology provide a better market solution. For producing this new breed of sensors, as explained further in Chapter 3, multi-core processing architectures integrating a new common processor with one or more specialised processors is needed. The multi-core processing architecture can provide extensive flexibility at a small extra cost in the mass production, which in turn will enable much greater market opportunity to help us to make use of the many so called sensor cross-road opportunities, see Figure 1.2 (Rashvand et al., 2008).

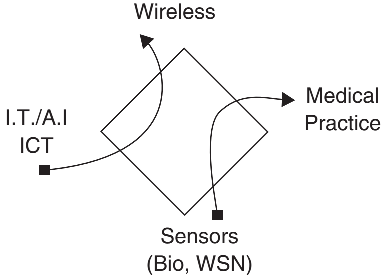

Figure 1.2 The telemedicine cross-road opportunity.

Cross-road opportunities represent techno-economical possibilities that become available under certain social demands in conjunction with a set of complementary technological feasibilities, which provide economical growth possibilities for industrial nations to take advantage of in order to build a better lifestyle whilst benefiting from associated economical success. Such short lived opportunities do not last for a very long period of time, often being lost due to upheavals of negligence and national or global disarray. Thus it is now that we have the best opportunity to deploy telemedicine style services to initiate further developments throughout the industrial nations.

Another new developing market opportunity is the integration of sensor technology with other applications using Internet and wireless technologies. Use of the Internet, these days counts as a unique opportunity for many new distributed services. We have many Internet enabled applications such as remote control systems that could benefit from the DSS. We also have the two fast growing technologies of radio frequency identification (RFID) and Internet of things (IoT) that, when used in cooperation with the new flexible sensors could offer great new market opportunities.

One of the immediate areas of application is an integrated solution with wireless sensor networks (WSN), where networking over the wireless enables a variety of application cases for the cooperation of sensors and RFID devices interconnected throughout the industry for various services at home, office, clinics and for other social activities. The wireless connection provides good mobility, but its use with the Internet makes the service go well beyond the existing borders. The safety and security aspects of RFID can also enhance WSN applications at the lower end of the market bringing a new integrated capability to the services. IoT, on the other hand is still new, but, due to its market potential of integrating various sensors through the Internet in various forms of fixed, moveable, wired and wirelessly connected devices, can bring more application opportunities in the near future.

1.3.2 Technological Developments

Here we scan a few potential technologies that make new smart sensors superior to the earlier generations.

Clustering

Despite their extensive communication and data processing capabilities new sensors are usually light and small. They can be spread around the area of interest in either forms of fixed or mobile to share their information with other sensors as well as the central controller. Due to their ad hoc unstructured networking nature they can form and reform their interconnection with other sensors to achieve their objectives with the minimum use of their scarce resources. For a special objective, or under a certain application scenario, they can easily form a cluster to accomplish their objective for the best result. The cases that make clustering useful depend on the circumstances. For example, wireless mobile sensors can position themselves and approach a target or as close as possible to the point of interest (PoI) in the media for collecting useful data. They can position themselves for a beam forming process to enhance their detection capability.

In the case of fixed sensors they can interact and detect a moving target and communicate in an optimum exchange of information. They can create a smart ambient for detecting activities or provide active interactions with the media or a reliable ubiquitous access service. In general, the clustering service brings a great feature of flexibility to the sensors.

Distributed Sensing

In order to demonstrate the general features of distributed sensing in practice let us consider a simple example where, a simple moisture-sensing device is located in the soil providing a reading for an open agricultural field. Using a single humidity sensor can provide a low cost solution supplying estimated information on the wetness in the soil. However, this sensor, due to the low validity of data, can only provide a poor reading as it can vary significantly upon the location of the sensor under very high natural and practical risks. Usual problems are wind, rain, sun, shade, proximity to the watering pipes and many other natural and man-made variants. Although such a system can almost do the work, if acceptable, it wastes a lot of water, and which, if followed up by processing of the data, can be tolerated, for proper engineering work this solution is far from perfect. However, using collective data from a multiple cooperating sensor system scattered around the field could improve the system's performance significantly.

In general, effectiveness of sensing depends on two inter-related factors of (a) distance between sensing detector and the sensing target, PoI usually referred to as vicinity and (b) accuracy of reading information in relation to the desirable data.

Often the first factor, in practical applications, is a handicap. It could be worse if we are dealing with a moving target or certain obstacles which separate sensors from the PoI. Using distributed sensors, a cluster of sensors or multi-sensor systems, this problem can be resolved. Also, considering the nonlinear signal loss, usually much higher than the order of 2, the problem of accurate reading could become very serious, therefore cooperative sensing can get closer to the target.

Tracking

In some cases a mobile target single sensing device, fixed or mobile, can get distracted by the noise and interfering signals and easily miss out on the target altogether. This feature can be extensively improved using a DSS. There are many advanced algorithms for distributed system, fixed and mobile, to trace a single or a multiple target effectively.

One of the most popular applications is video surveillance for home or plant security where often a mixture of fixed and mobile video sensors equipped with extensive signal and image processing can provide a very reliable surveillance solution.

One very interesting tracking application for the new distributed sensors is in chemical leak localisation. The writing of this book coincides with the BP oil leak in the Gulf of Mexico showing the scale of costs and troubles involved in such an accident. This incident shows how hard it is to detect such a leak and then the seriousness of the problem caused by a delayed detection and the impact to environmental health, sea life and heavy losses to the company.

Chemical leaks, gas or liquid, are mostly harmful and frequently happen in large industrial plants caused by corrosion and other decaying processes. Traditional solutions for detecting such leaks allocate a large number of chemical sensors fixed along the space over high-risk points and weak places mostly close to long pipes and inside processing chambers. Each sensor usually works independently to detect any possible leaks and set an alarm either locally or reported to the plant's central monitoring unit for immediate actions and recovery. Consider that chemical sensors such as odour detectors, which mostly simulate the human nose, are bulky, expensive and wasteful which normally pose a threat to a successful industry. Therefore, under financial pressure many operational managers are forced to compromise and to go along with some risk of not having full coverage. However, instead of a huge number of fixed sensors we can use very few mobile intelligent sensors circulating along some predetermined paths or random roots providing a more reliable sensing system and guarding the whole plant by sharing their findings so that more accurate detection can be activated through a multi-sensing method using smart nanotube gas sensors for a fraction of the cost.

Sensor Fusion

Fundamentally, gathering useful information, also called *data*, is the basic task of a sensor. The accuracy of data depends on the sensing system, stability of the domain and its usefulness. In some cases the collected data is utilised immediately to take an action, but in most cases it is accumulated for a collective decision. In many new applications, collected data is used at a variety of stages. Some are used for preprocessing and some stored in a centralised database for future further processing such as building up reliable statistical data. The usefulness of a sensing system could be compromised due to lack of (a) required accuracy and (b) reliability of data being read by the sensor. Therefore, over sampling, compressed sampling and other pre-processing of the data could become helpful.

The degradation of data cannot be limited to the noise and interference from the sensing signals, but depends on the original reading loss. This usually is caused by some practical factors such as the angle of detection, linearity of the signal and statistical status of the domain at the PoI. The errors and distortions caused by the interfering phenomena are traditionally removed using a filtering system, for example Kalman filtering for sensor fusion, but with new developments these complex processes can be easily compensated or disappear when using multi-sensing by enhancing the original reading of data from the domain.

Energy

Wireless and distributed sensors require a considerable amount of power and usually use local power resources, often batteries. This is often considered a weakness of WSN and other isolated sensing devices.

Though highly improved energy devices have been effective, many new developments have been helping us with this problem in four directions: (a) minimum waste of energy using energy-efficient algorithms, (b) efficient architectures using complementary metal–oxide–semiconductor (CMOS) technology and highly power efficient processors so that no activity wastes can be reduced, (c) highly efficient specially designed architectures and (d) making use of local energy generation such as energy scavenging and solar charging techniques to keep the device always ready for emergency activities.

For example, inefficient traditional style networking and communication activities usually consume a very high portion of the energy. Using cross layer techniques can save a great part of this energy.

Intelligence

The integration of limited intelligence in the third generation of sensors can boost up their applications. We have discussed some of their features under distributed intelligence in Section 1.4 and then throughout the book with applications cases. One of the most interesting applications of these sensors is the creation of smart spaces with clear cases of smart home, smart office under smart ambient. For example, we can look at an established case of using a large number of low cost fixed sensors spread around the area of interest monitoring a moving target. As shown in Figure 1.3 a basic two-dimensional array of fixed ultrasonic sensors fixed on the ceiling of the room can track a vulnerable person whose state of health is at risk and who is not able to call for help when they need it or if they fall. This simple and practical application of distributed sensors is discussed further in Chapter 6 under *smart home* for a better lifestyle.

1.4 Distributed Intelligence

Consider that a successful deployment of the new generation of distributed sensors can be closely related to the use of distributed intelligence, which is regarded as one of the key technologies for a successful global technological development.

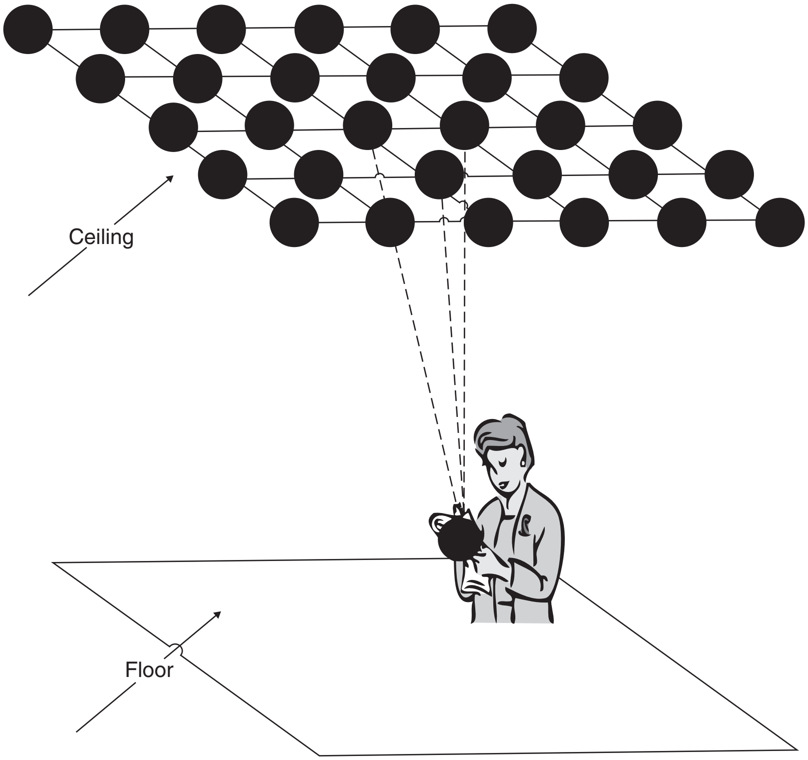

Figure 1.3 Smart home environment application, an example of adopting intelligence at home.

We now examine further developments of distributed intelligence through *process innovation*. Here, we look into the successful development of agent style distributed intelligence through innovation before devising a new method of maintaining the stability in a complex distributed intelligent system.

1.4.1 Innovation

We know by experience that a true *invention* is based on problem solving with a traditional definition of ‘a novel idea that has been transformed into reality or given a physical form’ is only a starting point towards bigger steps in the chain of invention to innovation to a socio-economical progress. That is, although without invention there is no innovation and therefore no social or economical progress, but only a few selective inventions featuring *feasibility* and fewer feasible inventions can viably enter the domain of innovation and then a bundle of cooperative innovations may trigger further social and economical developments. For turning an invention into an innovation some selective inventions should be tested upon their completion of the follow up steps under the process of innovation upon its traditional definition as ‘introducing something new or applying a new idea to meet our needs’ indicating two basic success factors of technology and market.

As the time goes on, however, the significant impact requirement of penetration into today’s complex, resistive and highly competitive dominating global markets is getting more difficult. We, therefore, need to re examine the process. In order to achieve our extended understanding of innovation we look at two historical views:

‘*He who will not apply new remedies must expect new evils, for time is the great innovator*’ from Francis Bacon (1561–1626), Philosopher of Science.

‘*Many essential human needs can be met only through goods and services provided by industry where industry has the power to enhance or degrade the environment; invariably it does* both’ from World Commission on Environment and Development, 1987.

Two immediate deductions:

Our existing survival depends on seeking new solutions for new and old problems because, due to the complex nature of controlling organisations, the industries cannot be trusted blindly, and new and progressive lawsuits are required to control the industries.

The first deduction indicates that we need to maintain the ‘problem solving’ as a basic process for new developments where researchers, experts and other key intellectuals should recognise ‘real, common and pressing problems’, understand the most suitable advanced feasible solutions for the most reliable design approach to promote new viable solutions whilst generating minimum or negligible side effects. These side effects or more correctly *innovation side effects* represent a significant factor in the process and therefore require proper attention.

One way to view them is to compare their similarity to the patterns of radiation intensity in a directional antenna delivering its highest power towards a particular direction through the main lobe. But, due to its imperfect design the antenna generates some smaller lobes in different directions causing interference for other transmission systems. In the same way that an innovation brings constructive impacts to society upon its primary lobe, the unavoidable, unwanted side lobes impose undesirable impacts onto society.

For two practical aspects of innovation side effects one needs to examine two factors: (a) *controllability* and (b) the management of the side effects.

When the pace of deployment is slow then both factors are manageable. That is, diffusion of innovation can be controlled and side effects can be gradually removed or converted into progressive and constructive developments, a case true for around 200 years.

The long awaited use of the steam engine made use of Leonardo De Vinci’s superior inventive designs. The socio-economical impacts of this major event then triggered a series of effective industrial developments with wider implications in all aspects of Western European societies: for a new industrial life, also referred to as *the first technological revolution*. This is when the progressive technological developments encouraged industrial nations to take on newer challenges, saving European life from the dark ages, a period which is often called *the great transformation* also known as the *Renaissance*. In that period, however, we experienced the innovation as a simple process and we had full control over all aspects of technological, economical and social developments.

As a century of industrial development continued, the impacts spread all over the globe, but at the same time all systems began to become more and more complex. However, then we were still dealing with non-intelligent and controllable systems within two main flagship industries of chemistry and electricity. Much harder, but just as feasible, further developments that continued for another century meant that we succeeded with *the second technological revolution*, enhancing many nations' quality of life all over the globe. Chemistry was then offering new materials previously unknown, such as plastic and fibre, and electricity enabled new ways of generation and distribution of power, light (Edison) and signals to carry information (Morse, Bell, Marconi) all gathering the new essence of a change towards *decentralisation*.

Since then another century has passed with many more impressive innovative ideas and large scale developments triggering many philosophers, economists and technocrats to look for the signs to mark the *third technological revolution*. To some degree, this expectation has been explained by the theory of *Kondratiev long waves* (KLW) featuring, a periodical half-century cycle, superimposed phasing out of innovation with economical booms and busts. Figure 1.4 shows the main factors of the theory. In order to justify their expectations the experts are looking for some key technologies with clear leading flagships.

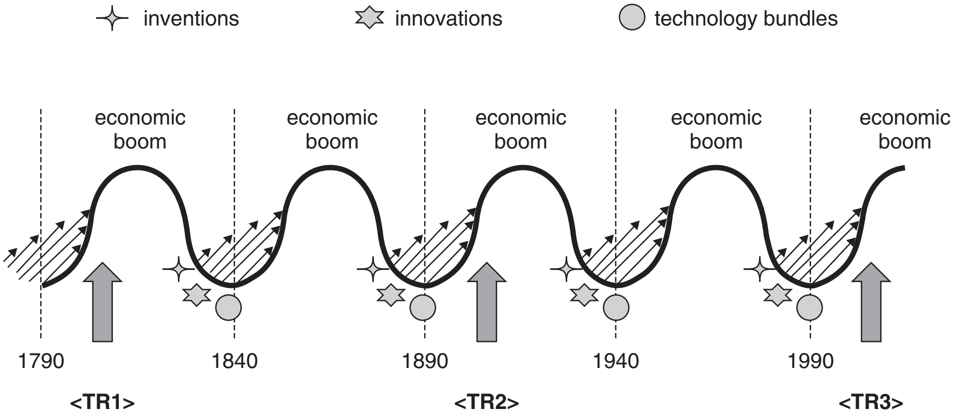

Figure 1.4 Kondratiev's long waves are accompanied by three technological revolutions. The symbols indicate inventions, innovations and bundling new technologies.

With the rapid growth of the telecom industry and continuous developments of micro computing under the flagship of the Internet, in the last few decades of the twentieth century many gathered their hopes upon ICT as a key enabler to deliver another technological revolution. However, as the impacts so far are not convincing enough we are still looking for more effective technologies and expect the new generation of distributed systems such as distributed sensors and distributed intelligence to be the answer. To support this claim we can explain a few important processes of dis-invention, intelligent agent and overlay networking before our proposal of a new quality control management algorithm (Open University, 1996).

1.4.2 Dis-Invention

Following our earlier lobe model of innovation, it is quite common that the excitement of the useful primary lobe could overshadow its side effects at the time of diffusion and will then be forgotten, to remain in society as an interfering process. Three possible cases of innovation side effects:

- passive and controllable, dissolve in time;
- active but controllable, need to be removed sometimes;
- proactive and uncontrollable, may grow in time.

If the problem of controllability is directly related to a system's complexity, then keeping our systems as simple as possible will always help. So, for our progressive technological developments we can remove the side effects by adopting one or both of the following tasks as required.

Keep complex systems under control by breaking down large systems into smaller ones whilst continuously looking for any significant side effects of the previous innovations and remove the harmful side effects through regular stages of dis-inventions.

1.4.3 Intelligent Agent

The most important aspect of using system 'intelligence' for DSS is accountability and therefore systematic manipulation of the data being collected for usability, decision-making and actions. In this form we can promote the implementation of AI in a new approach to integrate a kind of *distributed intelligent system* (DIS) for the use of *artificial intelligence* (AI) to build desirable DSS solutions. This can also help the development of smart sensors (and actuators) into the extreme engineering arts of building new microelectronic devices offering lower cost mass production of new autonomous sensors featuring independence, reliability, intelligence, embedded data possessing, cluster-based data fusion, ubiquitous connectivity and wireless energy scavenging features. That is, use of DIS can add an effective step towards nomadic device capability at system and middleware levels. This, in turn, could imply radical changes to the traditional architecture into new agile intelligent autonomous devices to form the DIS, using fewer simple, but highly effective interactive, loosely connected *distributed intelligent agent* (DIA) systems, which is an interesting development of AI in the distributed style use of agent technology. This follows the last four or five decades of AI being remerged into other forms of its associated technologies, interesting recent developments of AI are smart systems, intelligent agent (IA), in the form of multi-agent systems (MAS) and other agent-based intelligent systems for a wide range of applications such as embedded sensors, smart environments (Rashvand et al., 2010).

1.4.4 Deployment Factor

Deployment of a new system or a new service has always been a complex process. Now, with the advanced systems making more and more use of intelligent devices, the deployment process is becoming more unreliable and often risky. Therefore, implementing a viable system using any form of AI such as intelligent sensors, DAI, DIS and MAS or their combination with other systems should follow a controllable quality control procedure; otherwise, we should expect bitter experiences of non-productive trial and error and associated unavoidable loses.

That is, for a systematic approach to deployment, we should examine the following four system-level key requirements:

Trust – without trust and associated dependability, no proper use can be ensured and no natural global diffusion can be guaranteed.

Objectivity – overall effectiveness of an operation or a service heavily depends on the achievement of its fundamental goals.

Security – the ever-growing public fear of information insecurity due to poorly designed systems has created an unreliable infrastructure, so a new open system service needs its own independent information security control.

Stability – system intelligence inherits a natural factor of instability; therefore, control over critically important system’s parameters is essential.

The above four system-level requirements, TOSS for short, should enable the developer to follow various aspects of a system’s behaviour during its initial phase of deployment by opening a window of visibility for control, monitoring and management purposes during critical periods. For example, for implementing an intelligent sensor-based DSS application. The embedded intelligence nature of these devices’ system behaviour is complex in its nature; therefore, we can claim a quality delivery if our implementation includes all factors of TOSS in its procedure.

In addition, for implementing a DSS service, the deployment configuration could vary significantly from one scenario to another. But the service provider could benefit if he keeps and provides a visually integrated trace of all these TOSS factors as a top-level service, using a simplified design infrastructure to the clients. As we explain the details later, an unstructured networking infrastructure interconnects all intelligent components to a central controller using a reliable communication overlay, where each intelligent sensor is responsible for implementing some objective tasks whilst it makes the best use of its own autonomous capability for a maximum operational efficiency, effectiveness and survival.

To demonstrate this, as a guideline, we propose adoption of a deployment-based algorithm, where the ultimate goals and objectives, TOSS, are acquired through a linear progressive accumulation and distribution using an unstructured overlay system.

1.4.5 Overlay Network

The continuous monitoring of all actions and detailed operations of intelligent sensors in a distributed system put heavy demands on the scarce resources at the expense of wasteful activities to the system as a whole, which could be also disturbing for those sensors that can do most of their tasks independently. That is, the distributed sensors of an intelligent system operate normally in atomic style then they begin a fully controllable unit of an objective task under their own full responsibility. Therefore, a complementary, unstructured, overlay network is sufficient to compliment the atomic operations for coordinating the overall communications within the system. The concept of overlay is not new as it has been around for well over a century and is being extensively used in the telecom industry as part of network design and service delivery management with two different roles: (a) updating and adjustment of network resources as a response to constantly changing demand in operational networks and (b) security, quality control and monitoring of the provision of service upon faults, failures and measuring usage of the components and critical resource utilisation. The Internet is used as, or a part, of the overlay concept for updating information delivered to the distributed sensors: collection of information from the sensors for reporting their status or passing critical information such as hash security keys under classic service location protocol (SLP). More recently, the use of an overlay self-organising network shows a better maintained objective of complex networks under resilient overlay networks (RON). In some distributed sensor applications, distributed programming can benefit from swarm intelligence overlay-enabled cooperative networking, but practical simplicity of these networks resides in their uniqueness and application-based, data-centric, limited functionality used in their protocols such as distributed hash tables and sharing a database in sensor networking and spectrum sharing applications.

1.4.6 Deployment Algorithm

Having discussed the requirement for the adoption of distributed intelligence within the infrastructure of the DSS deployment process, here we introduce a simple but practical mechanism to help us with deployment of distributed sensor applications in all phases of design, test, manufacturing and implementation for both large and moderate complexity systems whilst maintaining our TOSS requirements. The new solutions make use of any well-established and dependable component such as smart sensors, intelligent sensors agents and an overlay mechanism.

Considering almost all active devices used in the third generation, sensors possess some degree of intelligence; for the sake of simplicity, in this algorithm we use the term ‘agent’. This phrasing also ensures that all sensor devices that are autonomous and possess intelligence should be included in the algorithm.

For DSS applications, some of these components have been discussed earlier in this chapter but mostly in Chapter 3. Whilst they commonly make use of a P2P protocol in the overlay network, this enables the agents to communicate with each other and with the central controller for maintaining a high-level cooperation. At the physical environment, each agent enjoys some degree of freedom for an efficient operation because of the fact that each member is required to operate reliably and securely in order to provide two sets of predefined complementary functions that are interactive and self-controlled. Provision of a simple debatable or distributed lookup-table (DLUT) translates the system’s objectives into an individual agent’s task table, which can vary extensively from one application to another and can be defined based on the particularity of the application.

The agents, being either individuals, independent sensors, or representing a cluster of sensors, should face their own, usually unique and dynamic, operational environment and use their own limited but fully controlled capability to achieve their own part of the goal as listed on their task table. Equally, any errors or miscalculations being injected in the design phase, in the translation, such as human error, or due to the drastic changes in the operational environment is converted into a malfunctioning for the agents, especially if the agents are empowered with extensive autonomy or operating under advanced natural algorithms such as evolutionary or swarms are converted into corrective operational objectives and then adjusted and redistributed by the central controller (Weynes 2010).

Process Convergence, Divergence Ubiquitous Access (CDUA)

Although using the integration of distributed intelligence in a MAS style DSS application well behaved agents opens up whole new desirable features which can enable the provisioning of superior solutions for many new applications, in practice, under the realistic circumstances of human errors, unpredictable operational environment and risky behaviour of the agents we need to safeguard the whole process without missing the main target of maintaining any critically important requirements in TOSS criteria.

We then propose an effective superior method for removing unpredictable destabilising interferences through a top-level system stabiliser to maintain a smooth overall system operation. This method based on a high-level quality control system can be implemented using three main complementary processes of convergence, divergence and ubiquitous access (CDUA) control mechanism.

Here we explain CDUA method and its use for implementing a complex distributed intelligent agent-based application to provide a reliable infrastructure to stabilise a complex system to operate within minimum risk margins. In this system the central controller works with many agents and is set to achieve a set of defined system's objectives. In the same way that a distributed agent can be adopted to work under different environments and carry out different tasks, some unique and some common, only its behaviour changes upon the system's objectives. Though all agents are autonomous in their detailed operation, these decisions are shared through the central controller and their tasks, usually a subset of system's objectives are allocated centrally. The overall control and deployment of tasks and objectives, however, is shared between the central controller and the agents. In other words this process of implementation follows a sequence of three complementary phases: (a) convergence of objectives and resources, (b) distribution of objectives translated into agent tasks and (c) provision of ubiquitous access through an unstructured network enabling ad hoc any required connections for monitoring, exchange of information and mutual decisions.

Convergence

This phase is normally divided into two parts of a generation-compilation of a long objectives list (LOL) and the estimation of availability and use of resources and associated optimisation processes.

Long objectives listing (LOL)

Having the ultimate set of goals provisionally defined for an application scenario, the centralised controller compiles the system's objectives accumulated from all agents. These are then combined and integrated into one feasible LOL to be managed by a central controller. This action of convergence removes the heavy burden of stability from agents' lists. LOL usually varies with time, application type, the environment and other variables such as a moving target or agent's mobility. Due to the natural flexibility embedded in the process, the convergence plays an important role in the system's performance.

Resource optimisation

At its top-level optimisation LOL requires the collection of all available agents' resources and their capabilities. Deployment of a mature technology, for example, can be listed more accurately and allocated to slower agents for lesser control overheads whereas new, immature and less known methods can work better with faster agents. In general, we need to consider taking the following actions prior to an optimisation process:

- a measure of processing media;
- update LOL regularly (if adaptive mission);
- build a working agent task table (ATT);
- convert objectives into agent-based tasks (*objective task converter*, OTC);
- identify risks, critical bottlenecks and urgent tasks (RCU).

Task distribution

This phase is the divergence part of the CDUA algorithm. Considering that all tasks should be carried out by agents working under different conditions, the converting system objectives LOL into individual agent objective tasks (AOT) and associated delegation processes normally requires a good application specific distribution algorithm. To ensure timely outcomes under minimum use of resources we need to adopt an optimised distribution mechanism for converting LOL into agents AOT. For this use of simple and mature methods is recommended whereas complex methods could lead to risky behaviour and reduced viability. Best advice for this stage is to avoid the use of any immature methodologies and avoid employing any risky high performance methods.

Ubiquitous access infrastructure

A real time deployment of advanced applications using distributed intelligence requires a highly reliable cluster based on an ad hoc networking infrastructure. Communication between intelligent agents to carry out the tasks in cooperation with the central controller is vital to achieve the system's objectives whilst maintaining the system's stability. Gathering reliable information on progressing tasks and on the behaviour of individual agents, essential requirements of the system should be examined regularly.

In order to be able to maintain a minimum, but always available connectivity a ubiquitous access infrastructure is required to enable both direct and indirect dialogues for exchange of data between all active components, for example overlay. This connectivity therefore is considered an essential part requirement for a CDUA implementation.

Due to the superior capability embedded in this infrastructure any unpredictable faults, interferences and shortcomings are systematically converted into delays in the process as the system is trying alternative routes. That is, as long as the system is in operation and a minimum ubiquitous access of a by-pass mechanism is working the embedded strategy should sub-optimally use some alternative paths for delivery

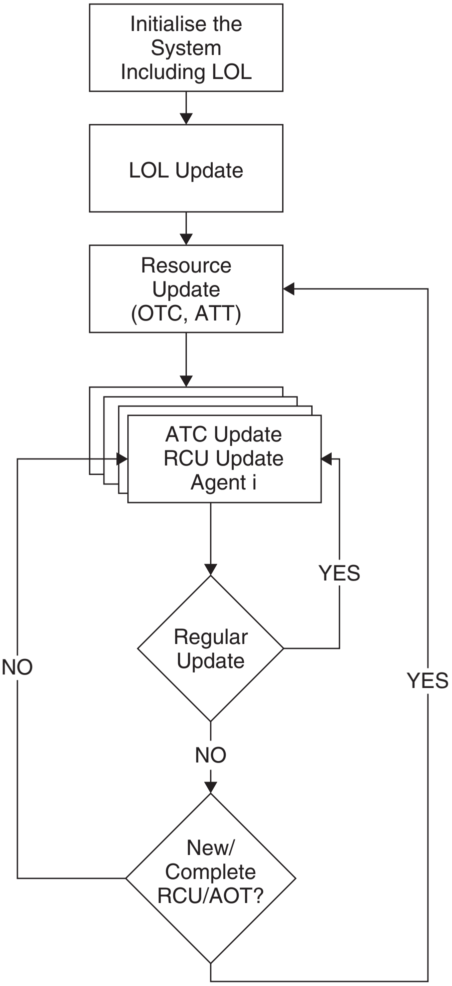

Figure 1.5 The operational flowchart showing the main process involved in Convergence, Divergence Ubiquitous Access (CDUA) algorithm.

of data. The main functions of the main processes of convergence, divergence and ubiquitous access of the proposed CDUA method are shown in the flowchart of Figure 1.5. Due to generality of CDUA algorithm further details are provided in various typical uses of distributed intelligent sensors in appropriate case studies and applications scenarios in Chapters 4 to 8.

1.5 Classifying Application Areas

With a common understanding of sensors and their applications being *'too many sensors too many applications'* one appreciates the need for a better understanding of this versatile technology and the associated woven treads of sustainability throughout other industries with *three* practical classifications, including our traditional grouping of dividing sensors upon their sensing domain.

Therefore, let's have a look at three application-based classification groups: (a) traditional domain-based sensor applications; (b) mobility-based sensor applications and (c) intelligence-based sensor applications.

1.5.1 Domain-Based Classification

Classification of the applications upon the source of transduction in many naturally involves the application media. For example, a chemical sensor normally involves the chemical industry and therefore being grouped as a class of chemical application it provides a helpful perception in the right direction. The five common overlapping domains are:

- physical sensors;
- mechanical sensors;
- chemical sensors;
- electrical sensors;
- biosensors.

There are three general issues associated with the above classification. First, this classification cannot be unique or change every time there is a new development, secondly, many sensors make use of different properties of a domain so we have many overlaps and finally many practical sensors use multi-stage sensing to change their detection domain.

1.5.2 Mobility-Based Classification

One important/effective/practical and useful grouping of new sensor systems is based upon their mobility feature. This simple but very effective classification can help to divide sensor applications into four groups, whether upon the sensor or the target, as in the sensing media, and relatively moving or fixed. See Table 1.1.

Table 1.1 Four mobility based classes of sensor applications

Target	Sensor	Notes
Fixed	Fixed	Relatively fixed, large and complex applications
Moving	Fixed	Embedded solution, smart media applications
Fixed	Moving	Cooperative sensor solution, industrial and monitoring applications
Moving	Moving	Target tracking applications using intelligent sensors

1.5.3 Intelligence-Based Classification

This classification of sensor applications makes use of the grouping discussed in Section 1.2, the historical sensors development with three classes of applications for TST, SSD and DSS.

This classification can be regarded as intelligence-based grouping. That is TST applications, like traditional sensor solutions come with minimum basic intelligence and normally operate in isolation with their full capability composed upon their transduction sensing and/or actuating process.

TST Based Applications

Upon their definition the TST sensors' main objective is the conversion of the phenomena of interest of the target media into a useable form of information with the minimum errors and disparity from the original phenomena's measureable data. Any extra enhancements will then be regarded as a bonus and helpful to the process, but normally not expected, because with the system level of the application a later process is expected to apply a further process before making use of the sensor's information.

This class of sensor application covers the widest and most versatile group of sensing devices including well-established heavy duty industrial, automation traditional, medical sensors and specialised sensors and actuators where the complexity of transduction inhibits their viability for cost effective mass production. Some require work under enormous constraints and operational limitations during their use and cost effectiveness for large-scale markets.

For example, for measuring the temperature we have many sensing options of low cost electrical and electronic devices. These are easy to use and being made abundantly available at a cost of next to nothing. But, as a standalone application there is no potential market requirement unless being integrated with other phenomena, whilst most chemical sensors and biosensors can provide potential desirable applications and come with serious practical constraints restricting their use to only a few costly application cases. In general, viable TST applications suffer from many practical limitations including:

- Weak Data collection – Immature technology and poor transduction process reading due to lack of proper control over the media limits the application's capability.
- Physically awkward placement of the device make it hard to get close to the object or PoI in the media.
- Space limitations often restrict sensors to get to an effective place (e.g. human body).
- Restrictive signalling issues for the device or media can potentially limit application's capability.

- Operational complexity may affect usability of a sensing application.
- Power consumption and provision of energy could reduce an application's lifetime.
- Maintenance and access during the use could increase the cost and limit usability of these sensors.

Chapter 2 provides some description for new TST devices with potential integrated applications.

SSD Based Applications

Use of the generic term of 'smart' in 'smart sensors', commonly used for sensor device technology does not automatically mean 'device intelligence'. Smart could mean simple enhancement to the information provided in the electrical domain within the sensing device, further classic routine information processing in this domain, or it comes with self-configurability of programmability capabilities using a modular structure. Classic smart sensors provide a modular structure to include the following three main sensing functions of (a) interfacing the transduction process with an analogue source for gathering reliable information in an analogue electrical signal, (b) conversion of an analogue signal into digital and (c) provision of a processor bus structure enabling the exchange of information between various modules or units. We explain further details in Chapters 2 and 3, due to the fact that a single core processor is used to provide the overall control of the system as well as programmable capabilities for the remaining modular interfaces and other functions of the application, the degree of intelligence in these devices is quite restricted, which can get directly reflected onto the range of SSD-based applications which in turn get reflected by the mass production of the core device and therefore cost per unit and thus onto any SSD-based deployment venture project. The following points may be regarded as influencing factors for limiting SSD-based applications:

- Single core architecture cannot be versatile enough for the required variations of applications in practice.
- SSD design optimisation can be easily achieved using conventional processing architectures. This, however, comes at the expense of loss in performance.
- Conventional peripherals can be easily adopted to handle the sensor's common functions such as sampling, data conversions, information coding, protocols and basic communication functions. These deceptive cost cuttings can increase power consumption, reduce flexibility and therefore affect the application's performance significantly.
- Cost effectiveness of a mass production could be easily jeopardised if the final applications deviate considerably from the core process.

The early generation of smart sensors originally aimed to develop an optimised ‘single’ core device to serve virtually all sensor applications, forcing down the production cost to an ideal approaching zero can capture the maximum share of the global market. This idea, however, has proved to be too idealistic due to:

- Single core architecture cannot be versatile enough to cope with the required variations we need for applications in practice.
- Widening the scales of the market imposes higher generalisation to the core architecture which in turn leads to higher customisation costs to the final product.
- As the market expands emerging new applications demand new features bringing new variations.
- Emerging demands change the market behaviour with which a single common core cannot cope without frequent anti productive upgrades.

DSS Based Applications

In general, as mentioned earlier, the market boundaries for many new technologies like sensors are spreading rapidly from national or regional into global scales, creating new market forces of specialisation in a highly competitive market domain where quality and low cost (mass) production become winning factors. Therefore, SSD type single core mass production shows weaknesses, whilst a multi-core architecture approach supports intelligent DSS applications and can play a significant role for cost effective production of new applications upon their potential for significant reductions in cost, power consumption and size whilst enhancing right functionalities and features such as versatility, flexibility, programmability, configurability, packaging, distribution, and provision of the service during their term of service. New intelligent DSS applications using double or in some cases multi-core processing technology make maximum use of agent style smart sensors which are built around a structured integrated device with a common core processor for generic and common functions and one or two specialised modules most adequate to a specific application, ideally from an off the shelf set of modularly compatible complementary processors. For further descriptions of typical examples for these devices and associated architectures see Chapter 3.